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Radiographic Imaging and Tomography

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Abstract: Radiographic imaging and tomography (*Rad*IT) come in many flavors such as X-ray imaging and tomography (IT), proton IT, neutron IT, muon IT, neutrino IT, etc. We identify five *Rad*IT themes: *Physics, Sources, Detectors, Methods*, and *Data Science*, which are integral parts of image interpretation and three-dimensional (3D) tomographic reconstruction. Traditionally, *Rad*IT have been driven by medicine, non-destructive testing, material sciences, and security applications. The latest thrusts of growth come from automation, machine vision, additive manufacturing and virtual reality ('metaverse'). The five *Rad*IT themes parallel their counterparts in optical IT. Synergies among different forms of *Rad*IT and with optical IT motivate further advances towards multi-modal IT and quantum IT.

1. Introduction

Invented by Wilhelm Röntgen at the age of 50, X-ray radiography introduced in 1895 is the oldest form of radiographic imaging. It is therefore not surprising that X-ray radiography and its growing number of variants are the most mature and widely used among all radiographic imaging and tomography (*Rad*IT) methods. X-ray methods can serve as models for other *Rad*IT methods such as charged particle imaging and radiography, neutron radiography, and muon tomography. Similarly, different forms of optical imaging, with their even older history, provide useful references for X-ray and *Rad*IT in general. We use high-energy X rays and γ rays interchangeably here for photons with energies above hundreds of keV. Röntgen's work no only showed that X rays can pass through objects such as human hands that are opaque to visible light but also demonstrated, for the first time, that internal material structures can be revealed without invasive sample preparation such as cutting or slicing. We shall mention that, by using adaptive optics or wavefront shaping principle first introduced to astronomy, photoacoustic tomography based on visible light has been invented to see through a certain class of opaque materials including human organs with the potential for whole-body imaging [1–3]. Wavefront shaping microscopy is now increasingly used in medical imagery and ophthalmology for aberration correction of live tissue [4, 5]. 3D super-resolution deep-tissue imaging has recently been demonstrated for living mice [6].

X-ray radiography has now been extended to tomography or 'imaging by sections'. Tomography is powerful and necessary for inspection of objects much larger than the spot sizes of X-ray beams, and for reconstruction of 3D models of the objects. 'Digital twins' are a relatively new form of time-resolved 3D models of the objects, coinciding with the emergence of virtual reality and metaverse. Modern X-ray tomography is computerized, thus the name computerized tomography (CT), in order to integrate the data from a large number of scans. 3D models, including digital twins, are further enhanced by the continuous CT technology improvements in resolution and reduction in the scanning time to acquire the data [7]. We have also witnessed that X rays are just one form of penetrating radiation for non-destructive imaging and tomography. *Rad*IT have since been extended to shorter wavelength photons such as gamma-rays, to energetic protons, to heavier charged particles such as alphas (helium nucleus) and carbon nucleus, to electrons, positrons, muons, neutrons and even to neutrinos. In addition to inspection of common objects that are visible to naked eyes, *Rad*IT have also been used in the highest energy accelerators such as the Large Hadron Collider (LHC) to visualize complex subatomic structures known as quark-gluon plasmas. One recent success was the experimental discovery of the Higgs boson. Muon tomography is an example that relies on the natural sources of radiation for imaging and tomography. Natural sources of X-rays, mostly from outside the solar system as discovered by Riccardo Giacconi (Physics Nobel prize in 2002) and opaque to the Earth's atmosphere, enable X-ray astronomy. New cosmic X-ray sources including ultraluminous X-Ray Sources are continued to be discovered.

The term *non-invasive* or *non-destructive* is relative for X-ray and other forms of *Rad*IT. On the atomic and molecular scales, X-ray radiation is fundamentally *destructive* since for each X-ray photon that passes through an object and generates a signal on the detector, there are companion X-ray photons that have been absorbed or inelastic scattered by the sample, and may escape detection [We shall mention that instruments that cover the 4π detection solid angle are feasible, similar to high-energy particle physics experiments at CERN and elsewhere, even though 4π instruments are usually not implemented in *Rad*IT applications due to cost and other reasons]. X-ray absorption and inelastic scattering, both of which can deposit energy in the object, lead to destruction of molecular bonds, ionization of atoms, creation of free electrons and defects. The microscopic material changes associated with each X-ray absorption and inelastic scattering are typically limited to nano-meter or larger lengths depending on the X-ray energy. Meanwhile, such microscopic destructions may not cause significant change to the bulk material properties or functions, and therefore, the term *non-destructive* is approximate and scale-dependent. Meanwhile, if a sufficiently large number of X-rays have passed through an object to produce a high resolution image or a high-fidelity digital twin, the accumulative effects of many X-ray absorption and inelastic scattering may no longer be negligible even on a macroscopic scale for high resolution *Rad*IT.

The quantum physics framework for the interactions of radiographic probes with matter is mostly established by the 1930s, as summarized in Fig. 1. All interactions are fundamentally quantum, while at high energies, X-ray radiographic imaging usually treats the interactions approximately as if photons were 'particles' and they would move along 'ray'-like definite trajectories. Wave-like properties of X-rays are now frequently encountered in X-ray imaging and image interpretation, in part due to the availability of coherent X-ray sources such as synchrotrons and X-ray free electron lasers. Quantum complementarity of X-ray photons means not all properties of X-ray manifest simultaneously when an X-ray image is captured or measured, which poses interesting questions for data analysis and image interpretation such as phase retrieval. Meanwhile, the quests for more information and details nondestructively have led to high-dimensional imaging modalities such as time-resolved 3D (aka '4D') and even 5D+ methods. High-dimensional imaging and radiography require the capture of extra information about X-rays such as energy, polarization, in addition to their position and the time of arrival which are more traditional.

We emphasize five scientific and technological themes: *Physics, Sources, Detectors, Methods, and Data Science*, see Fig. 1 for a limited number of highlights of milestones for each category. No attempt is made here to be inclusive of all the major milestone in each category. *Rad*IT science and technology have come a long way since the times of Wilhelm Röntgen (1895, listed as a PHYS event) and Johann Radon (1917, listed as a DATA event). The cathode-tube X-ray sources have been extended to modern multi-km-long accelerators, synchrotrons, and X-ray free electron lasers [8]. In addition to x-rays, charged particles (such as protons and muons) and charge-neutral particles (such as neutrons and neutrinos) have opened up new vistas into objects large and small. X-ray films have largely become obsolete due to the introduction of storage phosphor plates, amorphous silicon (aSi) flat panel detectors, CCD cameras and lately CMOS imaging sensors. Many of these modalities use the 'indirect' detection mode where radiation is first converted to visible light using scintillators and then detected using optical methods. Direct detection

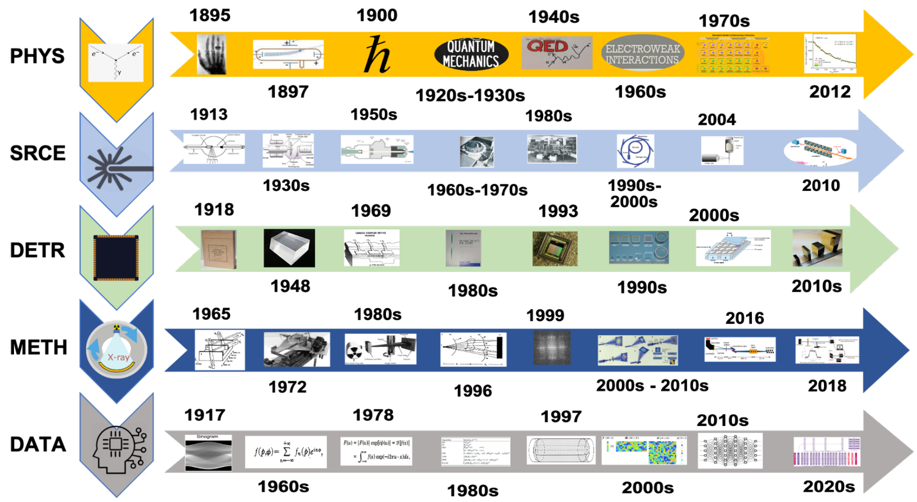

Fig. 1. We highlight some major milestones in *Rad*IT and sort them into five categories: Physics (PHYS), X-ray sources (SRCE), Detectors (DETR), Methods (METH) and Data science (DATA). For PHYS, X-ray discovery (1895), electron discovery (1897), Planck's constant (1900), the first comprehensive quantum mechanics framework (1920s-1930s), quantum electrodynamics (1940s), electroweak theory (1960s), the standard model of particle physics (1970s), and the experimental discovery of Higgs boson (2012). For SRCE, hot-cathode sealed X-ray tube (1913), rotating anode X-ray source (1930s), microfocus open X-ray source (1950s), the first generation of synchrotrons (1960s to 1970s), the second generation of synchrotrons (1980s), the third generation of synchrotrons (1990s to 2000s), and the first X-ray free electron laser for users (2010). For DETR, X-ray films (1918), Tl-doped NaI scintillator (1948), charge-coupled device or CCD (1969), commercial imaging plates (1980s), complementary metal-oxide-semiconductor or CMOS imaging sensors with active pixels (1993), more rare-Earth-element-doped inorganic scintillators such as Ce-doped Lutetium Oxyorthosilicate or LSO (1990s), commercial flat panel detectors (2000s), and high-Z semiconductors such as CdZnTe or CZT for radiation sensing (2010s). For METH, X-ray crystal interferometer with a monolithic silicon (1965), clinical demonstration of computed tomography or CT (1972), micro-CT (1980s), phase contrast imaging with polychromatic hard X-rays (1996), X-ray coherent diffractive imaging or CDI (1999), variants of CDI including X-ray ptychography (2000s to 2010s), X-ray ghost imaging using a synchrotron (2016), table-top X-ray ghost imaging (2018). For DATA, Radon transform and its inverse (1917), usage of Fourier Transform in tomographic reconstruction (1960s), phase retrieval algorithms (1978), iterative algorithms (1980s), 3D reconstruction method by Hildebrand & Ruegsegge (1997), compressed sensing (2000s), deep neural networks or DNNs (2010s), and constrained or regularized DNNs using physics and other information (2020s).

method using high-Z semiconductor including perovskites is emerging. Data and information science, including quantum information science, have breathed new life into radiography in the last decade. Traditional X-ray, charged particle, and neutron radiography R&D have been driven by medicine, non-destructive testing, material sciences, biology, chemistry and security applications. The latest thrusts of growth come from machine vision, additive manufacturing and virtual reality or metaverse applications. Space colonization may soon if not already place radiography technologies beyond the Earth's horizon. OSA (now Optica Society) DH3D imaging and applied optics conference provided an excellent forum to explore the synergies among visible light, X-rays, protons, neutrons and other forms of illumination in radiography, imaging and applied optics.

2. TRI 2021 and perpectives

We held a virtual mini-symposium TRI2021 in conjunction with the OSA (now Optica) Digital Holography and Three-dimensional Imaging Topical Meeting (DH & 3D), July 19-23, 2021. Nine invited talks, about twenty contributed oral presentations and a number of posters were included in the TRI2021 mini-symposium. More than twenty peer-reviewed full-length articles are included in the feature issue of Radiography, Applied Optics, and Data Science (ROADS). It is obvious that the data science aspect of *Rad*IT has drawn disproportionally large number of contributions, indicating one of the emerging frontiers in *Rad*IT.

In addition to the rapid growth of *Rad*IT enabled by data science, there are other exciting opportunities for all five themes of *Rad*IT. We shall point out ones with potential ties to quantum science. In physics, applications and better understanding of quantum physics could provide a new framework towards quantum *Rad*IT. In sources, further advances in luminosity of X-rays and particles could be augmented by source coherence, entanglement, and other quantum properties. In detectors, traditional emphasis on temporal and spatial resolution, detection efficiency, dynamic range, data yield could be enhanced by quantum measurement principles such as quantum non-demolition measurement. In methods, ghost imaging, ghost tomography, and alike are currently limited in part by the availability of the sufficiently bright sources of X-rays or quantum charged particle sources. In data science, quantum-physics regulated algorithms such as deep learning or data processing based on quantum hardware such as quantum computers may motivate further innovations and collaborations.

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